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Shallow geothermal energy integration in district heating system: An example from Serbia

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ABSTRACT

Integration of shallow geothermal energy could effectively contribute to long-term improvement in the energy supply systems by slowing down the growth of energy consumption, changing the structure of used energy sources, and by modernizing communal energy infrastructure. Such integration is one way of addressing sustainability goals, ensuring better energy security and economic competitiveness, and making a contribution to environmental protection efforts.

This paper examines the integration of local geothermal potential in the northern part of the Republic of Serbia and assesses the implications of using geothermal heat pump technology in a district heating system. This analysis considers different aspects of the proposed application and evaluates the environmental sustainability and viability of utilization of geothermal heat pumps for district heating.

Energy, economic and environmental performance was assessed for infrastructure that supplies 1274 properties in collective residential building segment located in a densely populated city area. The assessment quantified performance in key energy, economic and environmental categories, focusing on the use stage of the system's life cycle. The main benefit of the geothermal heat pump system is the reduction of the inlet primary energy by at least 30% by avoiding the use of almost a million cubic meters of natural gas per year. This also results in a competitive energy cost of 17 EUR/MWh, an investment with internal rate of return of up to 38%, and a discounted payback period of 4.9 years.

The geothermal heat pump system can bring energy and economic benefits but unfavorable environmental impacts, mainly due to the unfavorable electricity generation mix in the Republic of Serbia. The existing natural gas driven system was found to have lower impacts across all indicators but terrestrial eco-toxicity, natural land transformation and fossil depletion. In the climate change impact category, the existing system's impacts are 82% lower than those of the geothermal system.

1. Introduction

In the European Union (EU), heating and cooling account for approximately half of the energy demand [1]. In response, a key EU strategic document promotes decarbonization targets (also mandatory for countries in the accession process) related to the reduction of primary energy use in the building sector and substitution of decentralized fossil fuel based systems [2].

Despite the great importance for society, revitalization efforts in district heating systems (DHS) in developing economies like in the Republic of Serbia have seen slow in adoption [3]. DHS is an energy infrastructure capable of integrating locally accessible shallow geothermal energy sources as well as clean and efficient energy technology into the building sector, delivering a year-round low-cost heating solution [4].

DHS can contribute to the building sector by improving energy efficiency and allowing for integration of renewable energy sources. The integration of DHS with renewable energy sources has been shown to lead to a reduction in the carbon footprint and resource depletion [5]. Bartolozzi et al. found that a motivation for a DHS development are environmental benefits, in particular, DHS has the potential to reduce energy use and associated greenhouse gas emissions, stratospheric ozone depletion, and acidification [5].

In the review article of global utilization of DHS for heating and

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cooling, Werner highlighted the following needs: wider utilization in residential buildings, use of heat recycling and renewable heat sources, better commitment to clean technologies, recognition of CO_2 emission reductions and rising awareness of the DHS benefits [6].

The significance of low temperature networks in DHS was demonstrated in a study by Elmegaarda et al., where the authors suggest that the best low temperature system is a system with heat pump utilizing refrigerant R134a, efficiently decreasing the heat loss from piping and increasing the system's overall efficiency by 25% [7]. Furthermore, low temperature DHS network allows for an easier integration of renewable energy and other heat sources and enables better heat distribution efficiency [8]. A decentralized substation solution for sanitary hot water (SHW) supply in low-temperature DHS brings substantial benefits when compared to conventional DHS. Another study by Yang et al. demonstrated better performance on distribution temperatures under 50 °C, while the decentralized solution consumed less energy and cost less [9].

The use of ground source heat pumps in a residential district energy system have previously been found to be a favorable option from an environmental impact standpoint over a 25-year time-period [10]. Life-cycle costs have also been previously assessed [11], suggesting that ground source heat pumps are the most cost-effective solution when compared to other alternatives. The same authors also conducted a sensitivity analysis which proved high profitability of the ground source heat pump systems in residential building applications.

Two studies have assessed the environmental impacts associated with the operation of hybrid photovoltaic and solar-thermal systems using life cycle assessment (LCA) [12,13]. The authors highlighted satisfactory energy performance of the systems and found them to be more energy efficient when compared to conventional solutions for domestic applications, with considerable aggregated environmental impacts in the operational phase of their life cycle.

Petrillo et al. [14] considered sustainability of an integrated renewable energy system using LCA and suggested that it is necessary to include all variables that influence the economic, social and environmental issues. Similarly comprehensive approach has been applied to assess the technical and environmental performance of a solar water heater system [15]. The approach of concurrent analysis of economic and ecological characteristics for renewable applications was demonstrated by highlighting the high and dominant influence of local circumstances, like energy prices and source characteristics [16].

Uncertainties in performance prediction and site-specific circumstances create engineering challenges that many initiatives for energy infrastructure revitalization are facing today, especially in complex DHS [17], and SHW supply [18]. Therefore, successful application and associated risk identification can be done using a comprehensive performance evaluation from different aspects. As demonstrated by Luo et al. [19] and Chang et al. [20], such approach is valuable for design, analysis and operation of DHS using ground water heat pump (GWHP) utilizing shallow geothermal potentials.

1.1. Approach and objective

This paper demonstrates a cross-evaluation approach for the operation phase of DHS, combining LCA and cost-benefit analysis (CBA) of two comparative energy supply systems for district preparation of SHW. This means that energy, economic and environmental issues are considered simultaneously during the operation of modern energy systems. The two systems subject to comparison in this paper are the hot water condensing boiler (HWCB) system and the cascaded GWHP system used for SHW preparation in DHS.

The presented paper uses combined approach to assess the transformation process toward low temperature DHS by using local and renewable resources. The paper intends to focus the analysis to the use of GWHP in a DHS serving residential buildings, by examining its energy performance, cost affordability and environmental impacts for the operational phase of its life cycle and for a specific location. The holistic approach chosen for this analysis can reveal performance implications, expectations, perception, and the value of the service provided by these systems.

The intention of the paper is to establish an appropriate and replicable conceptual model considering site-specific circumstances and to present a case study application of the model. The findings of the presented study are specific to the presented location circumstances. The case study circumstances include an unfavorable energy mix in the production of electricity, an unfavorable price parity of natural gas and electricity, underdeveloped procedures for managing and maintaining energy infrastructure, unfavorable financial circumstances (e.g. high discount rate and lack of subsidies) and absence of management on the demand side.

The case study findings can be used to inform business and policy decisions in the Republic of Serbia., while the presented model may be used as a guideline for design and planning or for evaluation of the feasibility and viability of similar energy technology integration in other locations.

2. Case study district heating system

The analyzed case study DHS belongs to the public company Grejanje located in Pancevo City, Republic of Serbia. The heating fluid providing heat to the DHS substations comes from the local heating plant KOTEZ.

The residential neighborhood and associated district heating system were built in the early 1980s with the intention to provide supply services for heating and SHW to all inhabitants. The distribution network consists of a three-pipe system, where one pipe brings heat for space heating, the second pipe carries SHW, and the third is a common return pipe. The properties served by the distribution network are multi-story residential buildings with an average of 1.66 users per apartment.

2.1. Description of the energy demand

The analyzed energy consumption is related only to SHW preparation and associated supply infrastructure, as the most inefficient segment of the DHS. There are currently 25 residential substations that supply 2121 users throughout 1274 apartments. All thermal substations for the preparation of SHW are equipped with plate heat exchangers of suitable capacities and 5 m^3 accumulation tanks.

The current operating temperature regime of the existing SHW is 75/40 °C. According to the decision of the municipality officials, the public company Grejanje is obligated to deliver SHW to customers at temperature of 45 °C and by volume of 80 L/user. Current consumption exceeds this value according to the technical design guide based on Standard SRPS EN 15,316, for maximum requirements.

Fig. 1 shows the average daily profile of SHW consumption distribution. Presented profile of SHW consumption shows certain variations throughout the day, which points to the need for a system of increased flexibility. This is a real challenge for the efficiency of the present supply infrastructure.

Over the period of a week, in workday (i.e. Monday to Friday)

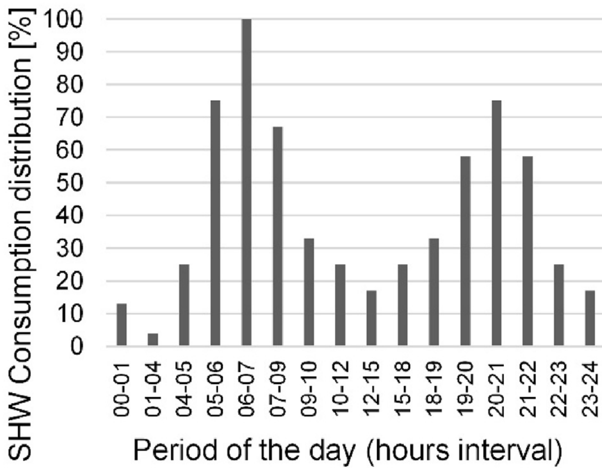

Fig. 1. Daily average profile of SHW consumption.

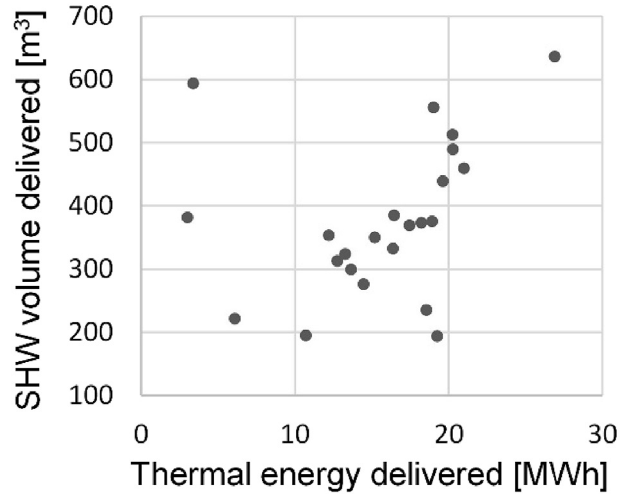

Fig. 3. Deviation of delivered thermal energy and SHW during the month of August.

consumption profile is at the level of 80%, while the weekend level is at 100%. At the annual level, from November to February the consumption is at 100%, while the months of March, August, September and October are at 90%. The minimum requirements (80%) are in the interval between April and July. The data was collected during an energy audit performed in collaboration with the local heating plant KOTEZ and the public company Grejanje.

2.2. Delivered thermal energy and water volume

Fig. 2 shows the recorded data for the month of August read from the heat meters in 25 substations within the system (23 residential facilities). In addition to thermal energy delivered, associated monthly SHW volume delivered are also shown in Fig. 3. The month of August was chosen for the analysis as the most unfavorable month for operation because the system is in regular operation, engaging entire infrastructure, all operators and all related services (generating the fix expenditures and distributive energy losses), while the SHW delivered volume and associated revenues are minimal. When considering the additional thermal energy consumption during the winter months, these values need to be increased by an average of 20–25% as compared to summer months. In some cases there are disparities in the thermal energy and SHW volumes delivered, as shown in Fig. 3. The deviation is approximately 20% across all substations with the exception of two substations with a high deviation. The two special cases are related to two nursing home facilities that do not have the same needs as the other 23 residential facilities. Other deviations are the consequence of an undeveloped demand side management which affects energy performance and makes prediction uncertain and unreliable.

The averaged and specified thermal energy delivered per substation is about 15 MWh/month, while the SHW volume delivered is about 390 m^3/month. Thermal energy consumed per household member is 178 kWh/month, while SHW consumption per household member is on average 142 L/day. This data shows a very high value of SHW consumption per user and per day, which is 78% higher than the standardized value (80 L/user/day).

Fig. 4 shows the recorded monthly consumption of natural gas for the preparation of SHW by the DHS. The monthly profile shows variations within the range of 20% and the month of August as the month with the lowest demand.

The total consumption of natural gas for the analyzed year is about 910,000 m^3, which corresponds to 7750 MWh of thermal energy. The average daily consumption of natural gas is about 2500 m^3, or about 22 MWh of thermal energy.

The source energy consumption through combustion of natural gas in the boiler for the month of August amounts to 559 MWh while the average of the measured values in all substations is 378 MWh. This means that the efficiency of the distribution network under summer conditions is 68%.

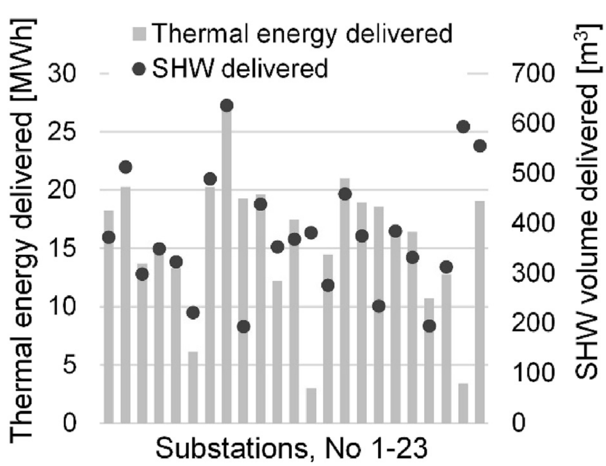

Fig. 2. Thermal energy and SHW volume delivered at each substation during the month of August.

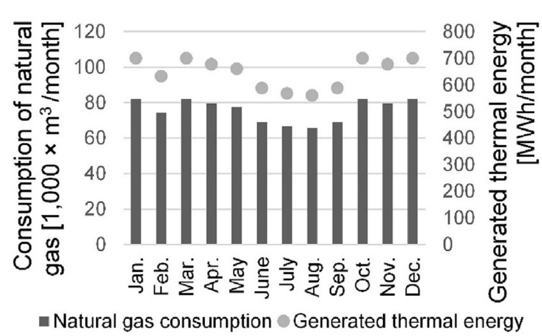

Fig. 4. Monthly consumption of natural gas and energy generated for preparation of SHW.

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2.3. Analysis of the current operating performance

The existing SHW preparation relies on a 7 MW natural gas driven hot water condensing boiler (HWCB). The current boiler capacity is several times higher than the current need, from 1.5 to 2 MW of thermal power, with breaks in operation of up to 16 h/day.

An energy audit of the HWCB was conducted in order to determine the actual performance of the boiler and to create a baseline scenario. The following parameters were independently investigated: boiler operational performance, occupation dynamic, capacity engagement, flue gas composition and conditions of the plant and its subsystems. The techniques used for this audit included a physical audit, performance metering, internal monitoring records analysis, engineering calculations and direct communications and interviews about specifics and opinions with the operational staff in charge of the company's energy department.

During the energy audit, the boiler performance assessment was performed under controlled conditions of operation following testing and evaluation procedure based on the international standard EN 12,952–15: 2003 [21]. This includes a 2-h measurement (120 min is the time for gaseous fuels) with a defined load profile of the boiler that is raised every 20 min, starting from 30%, 40%, 50%, 60%, 70% and 75%. Results and findings related to the boiler performance are presented in Fig. 5a–d.

Presented parameters are used for establishing existing energy profile, necessary for comparative analysis.

The recorded increase of carbon monoxide (CO) is related to a problem with the design and adjustment of the burner. The excess air was adjusted by adjusting the air volume entering the system until CO was detected. The optimal value of air is reached at 30% of nominal power, while at higher loads, the burner demands more air. High CO values were detected at power levels where the air demand of the burner was not met. Since, airflow was not enough, CO has appeared in larger amounts. The highest power level of the burner was at 75% due to the burner's power limiter.

3. Problems with existing practice

Over time, the use of HWCB in DHS has shown sub-optimal performance due to large loses within the system. The loses are related to the operation of the large diameter return pipeline transporting relatively low water volumes, especially during the summer months. During the summer, the boiler itself operates in modes that are not optimal, generating heat with reduced efficiency.

The practice of allowing users to use SHW without individual measurement has also created issues for the operation of the system, resulting in financial losses for the company operating the DHS and consequently decreasing the quality of service over time. In the end, the number of users has decreased significantly over time due to dissatisfaction with the service. Currently, about 24 MWh/day or 1–1.5 MW of thermal power is required for the production of SHW in this DHS, which has a capacity of around 150 MWh/day and 7 MW of nominal thermal power. A consequence of a boiler operating at technical minimum is reduced energy, economic and environment performance.

The current operating mode of the pipeline is 75/40 °C which is not a regime recommended by today's standards and expectations for district systems.

4. Proposed heat pump solution

The proposed solution is an upgraded system for SHW preparation, where cascade arrangement of GWHP application is integrated and works in combination with the existing condensing

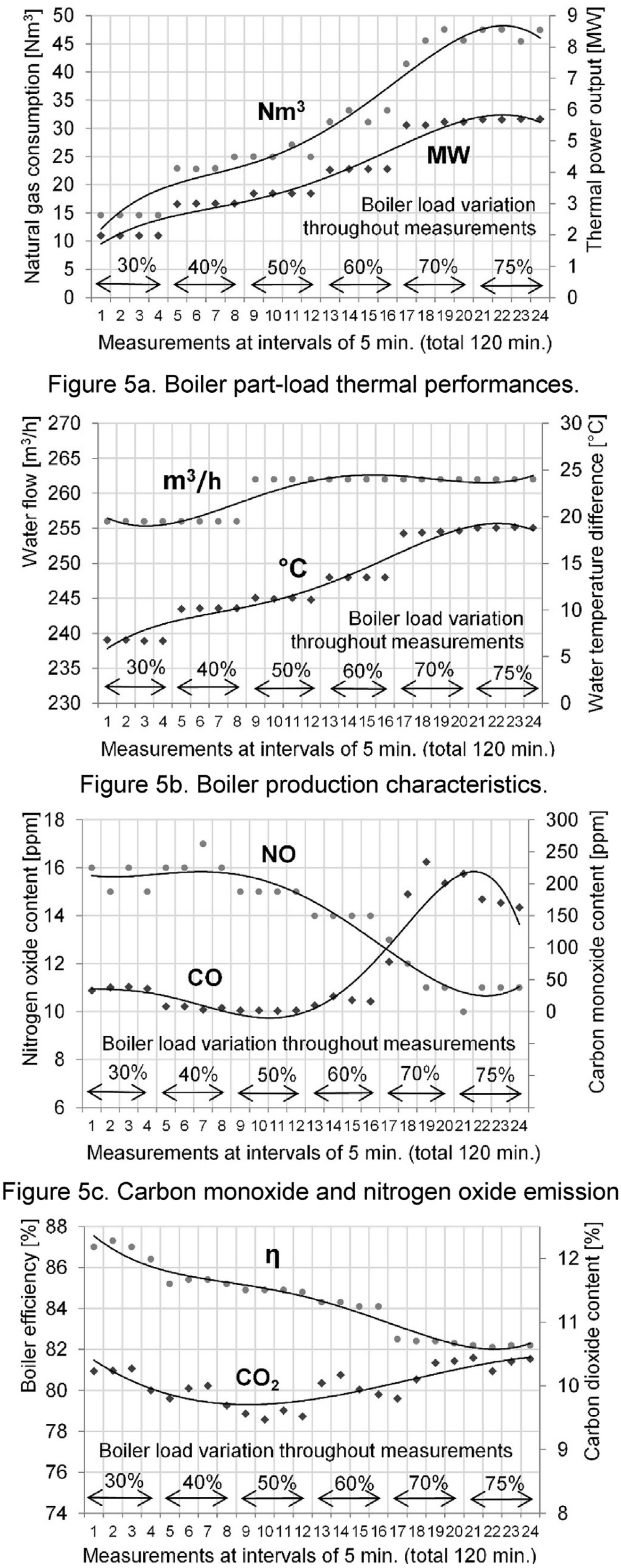

Fig. 5. a. Boiler part-load thermal performances. b. Boiler production characteristics. c. Carbon monoxide and nitrogen oxide emission. d. Boiler efficiency at part-load operation.

boiler. GWHP system is supported by a boiler to provide the necessary capacity and safety in the operation of the central preparation of SHW in central energy plant (Fig. 6).

The heat pumps' capacity requirements were calculated using the heat pump manufacturer's software tool and relevant specification and performance data sheets. The determinant operational criteria included the heating output, power consumption and coefficient of performance (COP) given for different temperature regimes and in accordance to EN 14,511. SHW demand is based on monitoring data and existing consumption data confirmed by local district heating department.

The central facility has two large-scale heat pumps (water-water type), with individual thermal capacity of approximately 330 kW, in total 660 kW. Capacities of the GWHPs correspond to the capacities of the wells and a temperature difference of 7 K. The temperature in the supply pipeline should be about 38 °C. In that temperature regime, small distributed GWHPs in substations can receive a 35 °C water temperature that corresponds to the maximum temperature that can be received by the GWHP in the evaporator of the standard version.

The second part of the system includes small-scale GWHPs, located in the substations. Two operational scenarios are evaluated, one with the heat pump runtime of 16 h/day (with breaks) and another with the heat pumps running continuously 24 h/day, for implementation during the unfavorable winter regime. Table 1 shows the SHW consumption data and estimated required capacities of the GWHPs in the substations.

It can be noticed in Table 1 that the consumption of SHW varies from substation to substation. The average capacity of a GWHP in a 16 h/day mode is 30 kW and 38 kW in the winter, 24 h/day mode. In order to meet the electricity network requirements (8.5 kW per substation) and economy and maintenance aspects (spare parts) for this type of GWHP, one variant of capacity of about 35 kW was selected. For substations with higher demands, the number of runtime hours increases or multiple heat pumps have to be installed.

Based on the previous analysis and calculation, the following heat pumps were adopted: two large heat pumps with heating capacity of 337.2 kW, total power input of 55.9 kW, refrigerant R134a, COP of 5.60, and 26 small heat pumps with heating capacity of 35.6 kW, total power input of 4.3 kW, refrigerant R410A, and COP of 8.27. Nominal operating water temperatures for inlet/outlet evaporator are defined at 12 °C/7 °C; inlet/outlet condenser water temperatures are defined at 30 °C/35 °C [30]. Data used for performance calculations are based on case-study design temperature regimes, with seasonal variations of evaporator outlet water temperature between 8 and 11 °C and condenser outlet water temperature at 38 °C and 50 °C, for selected GWHPs respectively. Fig. 7 shows calculated performance data for the GWHPs in the central plant. Fig. 8 then shows the GWHPs calculated capacity, production and expected COP [31].

Table 1
SHW consumption data for August and calculation of the required capacity of the GWHPs.

Substation	Household members	Dwellings per substation	Delivered energy [kWh]	HPs capacities for continuous or breakable operation [kW]
1	102	78	18,250	24.5–36.8
2	49	35	20,272	27.2–40.9
3	74	43	13,680	18.4–27.6
4	104	55	15,200	20.4–30.6
5	59	40	13,300	17.9–26.8
6	75	45	6120	8.2–12.3
7	74	46	20,292	27.3–40.9
8	112	65	26,910	36.2–54.3[a]
9	82	50	19,260	25.9–38.8
10	112	70	19,640	26.4–39.6
11	111	75	12,227	16.4–24.7
12	135	62	17,480	23.5–35.2
13	75	48	3025	4.1–6.1
14	106	47	14,480	19.5–29.2
15	108	56	21,030	28.3–42.4
16	94	52	18,950	25.5–38.2
17	73	35	18,572	25.0–37.4
18	109	59	16,470	22.1–33.2
19	65	43	16,400	22.0–33.1
20	82	40	10,740	14.4–21.7
21	99	93	12,790	17.2–25.8
22	135	80	3408	4.6–6.9
23	86	57	19,040	25.6–38.4
24	86	–	16,462	22.1–33.2
25	36	–	4200	5.6–8.5
Total	2121	1274	378,198	508.3–762.5

[a] Two GWHPs need to be installed.

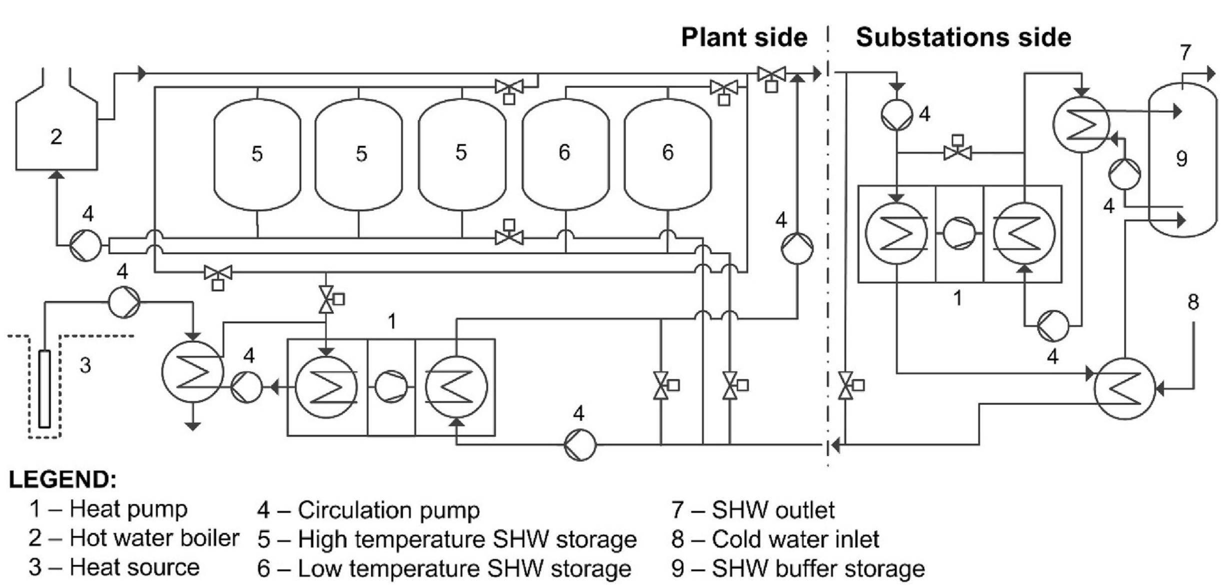

Fig. 6. Conceptual design of GWHP integration.

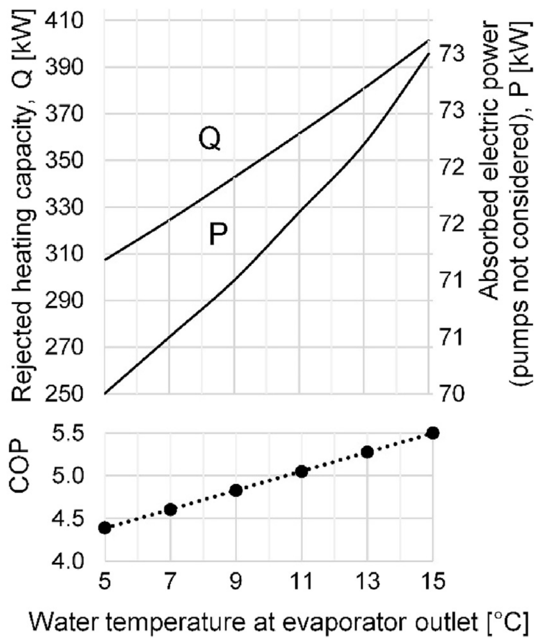

Fig. 7. Performance curve of GWHPs installed in central plant.

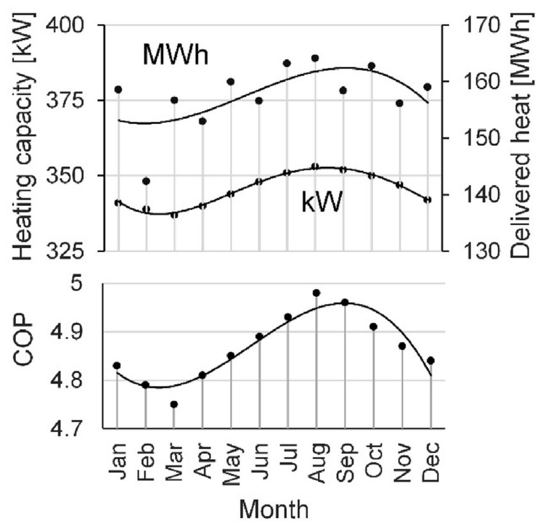

Fig. 8. Monthly performance data for single GWHP installed in central plant.

For the 26 small GWHPs in substations, the variations of performance in the heating mode are not significant due to stable temperature regimes between seasons and minor variations of temperature difference between source/sink (35/50 °C). The calculated COP is 7.7, heating capacity is 30.1 kW and power input is 3.9 kW.

Slight COP decrease is expected due to the anticipated increase in temperature differences as a consequence of rising heat losses in the distribution network over time. Furthermore, COP reduction can be expected due to the characteristics of the applied refrigerant, quality of the system controls, heat exchanger cleanliness, and the efficiency of peripheral equipment like fans and pumps.

5. Locally available geothermal energy

Although there is a great interest and governmental support for using local and clean resources in the Republic of Serbia, shallow geothermal capacities are not sufficiently used in the communal energy and building sectors. For this reason, new strategies and initiatives for the implementation of shallow geothermal energy technologies such as GWHPs are needed. A large and increasing share of fossil fuels in DHS is imported at high and increasing prices, which threatens the economic competitiveness and the security of energy supply for DHS.

In different site-specific circumstances, the economic viability of shallow geothermal energy projects is dependent on the balance between energy performances and associated costs [18].

One exploration well was drilled in order to check the shallow geothermal source at the case-study site. The site was evaluated for groundwater abundance to confirm the possibility of using GWHPs. In this first phase, hydrogeological parameters of producing well were determined based on the assessment of the geothermal potential. For this purpose, drill log (lithological profile) in the well zone was established and hydrogeological parameters with yield of the drill hole were checked (necessary amount of groundwater). Next, the hydrodynamic testing of wells was performed. The pump test results were used to determine the hydrogeological characteristics of the aquatic environment, the hydrogeological parameters of the wells, and the optimal regime of exploitation. Pumping was carried out with an electric submersible pump of 7.5 kW power at a depth of 16 m. The test was carried out with 2 pump capacities, 5.7 L/s and 8.2 L/s, and total duration of 4200 min with monitoring of the water level returning 120 min after test finishing. The capacities of the pump were determined and controlled by the volume method. The static groundwater level before the test was measured at 4.65 m below the surface of the terrain.

The results collected during the control pumping test were treated with a graph-analytical procedure, specifically Jacob's method. The method for processing pumping data are in the form of the diagram S = f (log t) [22]. Based on the results of the testing, the filtration characteristics of the aquifer are determined as the water conductivity coefficient (transmissibility) T (m^2/s) and the filtration coefficient K (m/s) using equations (1) and (2), respectively.

$$T = \frac{0.183 \cdot Q}{S_1 - S_2} \cdot log\frac{t_2}{t_1} \quad \left[\frac{m^2}{s}\right] \tag{1}$$

$$K = \frac{T}{M} \quad \left[\frac{m}{s}\right] \tag{2}$$

where $Q_1 = 0.0057\ m^3/s$, $S_1 = 2.55$ m, $S_2 = 2.65$ m, $t_1 = 5$ min, $t_2 = 2100$ min, and M = 22.7 m (total thickness of the aquifer layer).

By processing the data of the experimental pumping by the method S = f (log t) (shown in Fig. 9), the following values for T and K were obtained: $T = 2.73 \cdot 10^{-2}\ m^2/s$ and $K = 1.20 \cdot 10^{-3}$ m/s. Based on the maximum allowed input speeds, the operating capacity of the well (Q_{opt}) is recommended to be:

Based on the maximum allowed input water speeds, the exploitation capacity of the well is 600 L/min, or 36 m^3/hour, whereby the suction part of the pump must be installed at 17 m depth. By exploiting groundwater with this capacity, the following should be achieved: a stable operating regime of wells, a longer lifetime, and the stability of the pre-filter zone in the context of the groundwater flow toward well (speed of movement). It was also found that there are no influences of other water intakes on the well. The results obtained for a 55 m deep well are 36 m^3/h of water temperature at 15 °C. This corresponds to a capacity of about 300 kW for obtaining heat using groundwater-water heat pumps if the underground water is cooled by 7 K. The investigation has also determined that another 3 wells, one producing (source) and 2

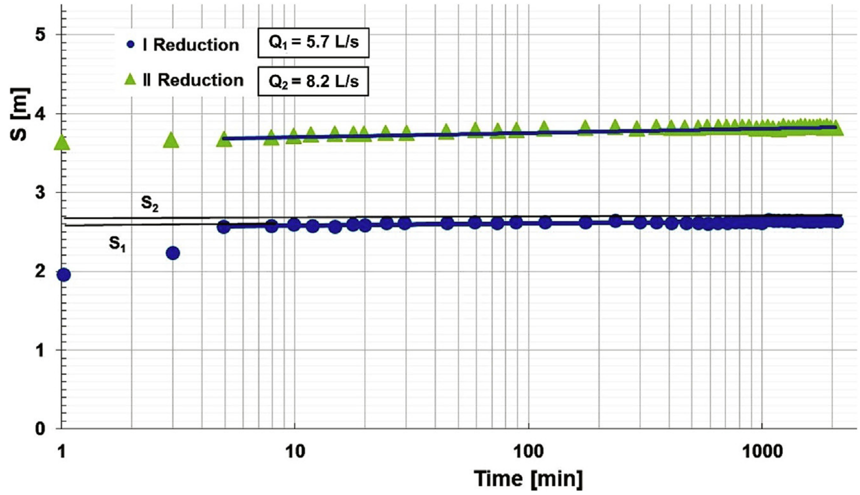

Fig. 9. Diagram of pumping test S = f (log t) − I and II reduction.

absorbent wells, can be drilled in the same location. This way the required capacity of about 600 kW can be obtained for the needs of the application of GWHPs.

The hydrodynamic test confirmed that the well can operate uninterrupted without signs indicating premature aging of the well. In this analysis, bore-hole logging measurements were carried out to define watertight and non-watertight environments as well as to determine their characteristics. An analysis of the drilling speed and drilled material was made and then compared with the results of geophysical bore-hole logging. In the construction of the wells, the filtration stability of the pre-filter zone and the laminar flow regime were considered. In applied “Kovach” criterion, the critical (allowed) input flow velocity was determined. This is one of the few criterions for stable exploitation. There are also no other nearby facilities exploiting the groundwater. Design working regime of the GWHPs should ensure a stable and uniform way of groundwater exploitation. Based on all of the above stated findings, there are reasonable assumptions for the stable operation of a producing well.

6. Energy and economic analysis

Energy analysis was performed in relation to the expected production of thermal energy, in accordance with the tested capacity of geothermal resource, for known end-using needs and dynamics, as well as according to the calculated heat pump COP.

Economic analysis was performed in accordance to the current market prices of equipment and necessary works and current price parity of natural gas and electricity. The price parity of the GWHP solution is very favorable in Republic of Serbia due to the undervalued market price of electricity and the market price of natural gas. The temperature regime used for calculation of the heat price is 75/40 °C for the existing supply scenario.

Table 2 shows the results of the cost analysis, showing that the total annual savings from operating the integrated GWHP system equal to 188,400 EUR/y. The main consequence was a substantial reduction of specific energy unit cost from 42 to 17 EUR/MWh.

The produced heat in the existing HWCB system was transported at 75/40 °C and the established efficiency of the network was 68%. It was estimated that the amount of network losses for this period was 1040 MWh. With the new GWHP solution, the temperature regime is lowered to 50/25 °C and efficiency is increased, reducing the losses to the level of 562 MWh. This implies savings of 478 MWh or 20,070 EUR for the period from May to October. Table 3 shows the network loss reduction during this period.

The savings are subject to change due to dependence on the quality of the maintenance, network operating mode, and potential reduction of SHW consumption from the standard range due to the newly planned metering and better control. For this reason, the network loss reduction was not accounted for in the savings. The network loss reduction could further improve the energy and economic balances and could reduce the consumption of natural gas of the existing boiler used as a support for the GWHP system. By achieving network loss reduction in the full extent, the existing boiler could even be completely excluded from the operation of the GWHP system.

The needed investment to put the GWHP system in place is estimated at 400,000 EUR. The following is the breakdown of costs for the entire system in percentage of total: Heat pumps in the heating plant (2 pieces): 18.5%; Heat pumps in the substations (26 pieces): 34.5%; Drilling and installing equipment for 4 wells: 25%; 30 m^3 buffer: 5%; Instrumentation, electrical, gas and control equipment: 2.5%; Assembly works and materials, integration of equipment in the existing control system, cabling, installation, tuning, testing, software upgrade, training, commissioning (guarantee test): 6.5%; Preparation of the project documentation: 4.5%; Mechanical, electrical, construction supervision: 3.5%. The CBA

Table 2
Cost calculation of the proposed solution on yearly base.

Supply scenario		Heat [MWh]	Electricity [MWh]	Energy price [EUR/MWh]	Energy costs [EUR]	
Existing boiler		7750	–	42 (heat)	325,505	
New solution	GWHP in central plant	3670	917	75 (Electricity)	68,782	137,101
	GWHPs in substations	4000	572	75 (Electricity)	42,864	
	Wells' pumps	–	37	75 (Electricity)	2775	
	Existing boiler	540	–	42 (heat)	22,680	

Table 3
Calculation of network losses reduction in the period May–October.

Temperature regime [°C]		Specific loss of pipeline [W/m]	Pipeline length [m]	Operating time [h]	Operating days [day]	Thermal losses [MWh]	Total losses [MWh]
1.	75	59.1	3220	24	153	698	1040
	40	29.3				343	
2.	50	34.3				406	562
	25	13.2				156	

included periodic annual costs (system maintenance, spare parts, performance control) up to 1%.

Adopted nominal discount rate is 8% and economic life is 30 years. Results show the internal rate of return to be anywhere from 33% to 38% depending on ±5% variations in energy savings predictions. Simple payback period is 2.1 years and discounted (dynamic) payback period is 4.9 years. Net present value and accumulated net present value are shown in Figs. 10 and 11 with the dotted-lines representing variations in annual savings by ±5%.

Projects for energy revitalization, reintegration and modernization are sensitive to numerous factors that are variable and uncertain in early planning and building phases. Among them, the dominant influences are the energy performance and related savings, as well as the prices of energy products on the market that significantly affect economic performance, especially the prices of imported fuels. For this reason, a sensitivity analysis was conducted for the key economic parameter, the Simple Payback Period (SPB), on the realized operational savings, the investments, as well as the price parity of natural gas and electricity.

The results shown in Figs. 12 and 13 indicate that there is a slight sensitivity of the parameter SPB on the price of electricity (i.e. increasing electricity 40%, leads to an increase in the SPB by 30%), and a greater sensitivity to the projected savings (i.e. a 20% reduction in the savings results in an increase in the SPB by 30%). Growth in the natural gas price will improve economic indicators (i.e. a 30% increase in natural gas prices reduces SPB by 40%). The most realistic scenario is that the electricity price increases by 20% and natural gas by 10%, in which case the SPB will remain unchanged in the amount of slightly over 2 years.

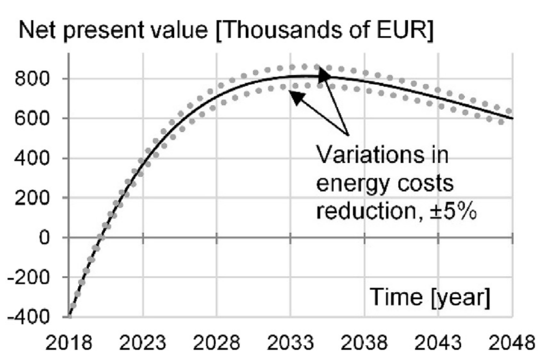

Fig. 10. Net present value.

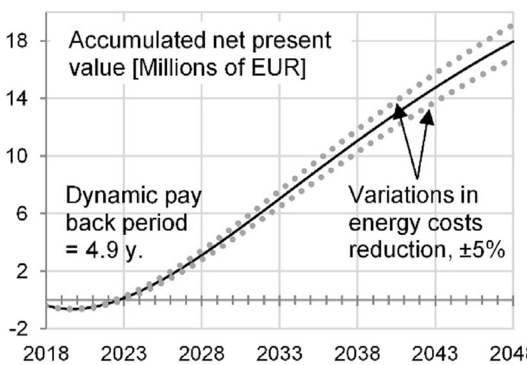

Fig. 11. Accumulated net present value.

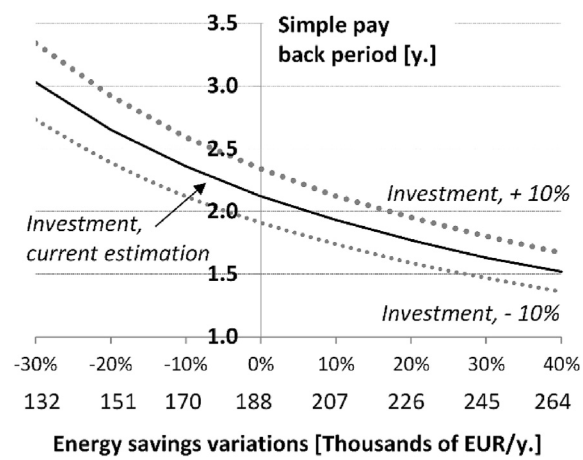

Fig. 12. Sensitivity on investment and savings.

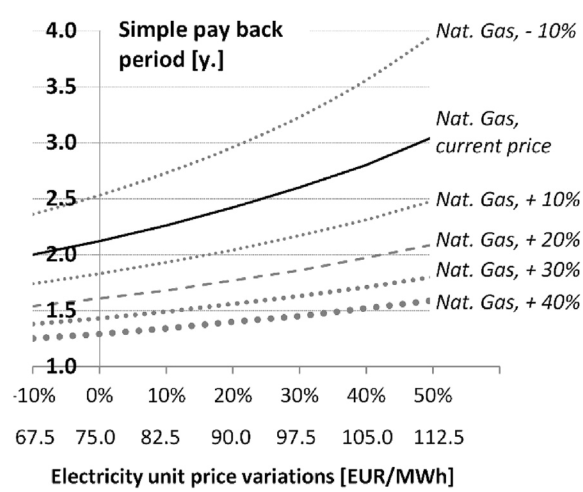

Fig. 13. Sensitivity on natural gas and electricity prices.

7. Life-cycle environmental perspectives

Life cycle assessment is applied as a widely used tool for the assessment of environmental impacts of products and services. The goal of this LCA was to compare the operational impacts of the

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GWHP system and the hot water condensing boiler (HWCB) system. The functional unit for the comparison was the supply of evidenced SHW amounts for the 1274 apartments over one year. The scope of analysis was limited to the operational use stage of the two systems, accounting for the electricity, refrigerant, and natural gas consumption. The raw material extraction, construction, maintenance, and end-of-life stages associated with the construction of the physical infrastructure of the two systems (i.e. pumps, pipes, etc.) were not included in this study due to lack of available data; however, this exclusion is not expected to impact the conclusions for two reasons: 1) the operational impacts can be up to 10 times larger than the material and construction impacts over the course of the systems' life cycle [25] and 2) the systems use similar equipment and piping networks, so the absolute impacts from infrastructure are expected to be relatively similar in both cases.

The life cycle inventory data for the supply of electricity, refrigerants, and natural gas was based on ecoinvent 3 data and includes all upstream impacts of the production and supply of these resources [29]. Electricity impacts correspond to ecoinvent's Serbian low voltage electricity unit process and natural gas impacts correspond to the “rest of the world” (RoW) low pressure natural gas unit process. The ecoinvent database contains production data for refrigerant R134a but not R410a, and no literature providing the environmental impact data for this refrigerant's manufacturing process was found. R410a is a mixture of HFC refrigerants R-32, R-125, and R-134a, according to Matsunaga [26]. The resultant mixture is produced by blending the refrigerants in storage tanks using a blending process with negligible energy use and emissions. The impacts from R410a manufacturing were, therefore, assumed to be the same as for R134a. Climate change impacts related to direct emissions of the two refrigerants were calculated by multiplying the mass of leaked refrigerants by the Global Warming Potential (GWP) of each refrigerant; i.e. 1430 kgCO2eq/kg of R134a, and 2100 kgCO2eq/kg of R410a [27]. Both refrigerants have zero ozone depletion potential for direct emissions. The leakage rate of refrigerants was assumed to be 20% [28].

The results are aggregated into ReCiPe midpoint indicators using the hierarchist scheme [24]. All of the ReCiPe impact categories and the comparative results are shown in Fig. 14; results for the 20% leakage rate and lower COP scenario show a conservative estimate for the geothermal district system.

The existing HWCB system was found to have lower impacts across all indicators but terrestrial eco-toxicity, natural land transformation and fossil depletion. In the climate change impact category, the existing HWCB system's impacts are 82% lower than those of the geothermal system. In one year, the existing system is responsible for about 390,000 kg CO_2 eq. emissions while the geothermal district system is responsible for 2.1 million kg CO_2 eq. The geothermal system's impacts are mainly associated with the use of the Serbian electricity mix, which is predominantly coal-based (71% of domestic production) [23], and the rest being hydropower. If only hydropower was used as the electricity source for this application, the impacts could be greatly reduced, for example, in the climate change category by up to 87%. In terms of system adjustments, the climate change impacts could be 14% lower if the pumps operate under higher COP and additional 3% lower if the refrigerant leakage rate was reduced from 20% to 15%.

8. Conclusions

This study consisted of LCA and CBA for a comparative assessment of two commercially available technologies for SHW preparation as an integral part of DHS.

Regarding the energy issues, proposed GWHP results in 30% primary energy reduction from the existing HWCB system given the SHW consumption is unchanged. Moreover, this reduction is reached by switching to fully domestic and local energy sources. Required thermal power is reduced by the fuel and technology substitution as well as by favorable distribution regimes (low temperature regimes, 50/25 °C). Additionally, energy and economic risks are reduced by eliminating dependence on imported fossil fuel, specifically by avoiding the use of 910,000 m^3 of natural gas annually. This makes the system and its operators more resistant to political and economic instability and variation in the market fuel prices.

An economic performance analysis revealed that the GWHP system can provide more competitive thermal energy prices in comparison with the existing HWCB system due to the utilization of shallow geothermal energy and cheap electricity. The thermal energy unit price was estimated to drop from the current 42 to 17 EUR/MWh of thermal energy (60% cost reduction). The main reason for the cost reduction was the atypical price parity of natural gas

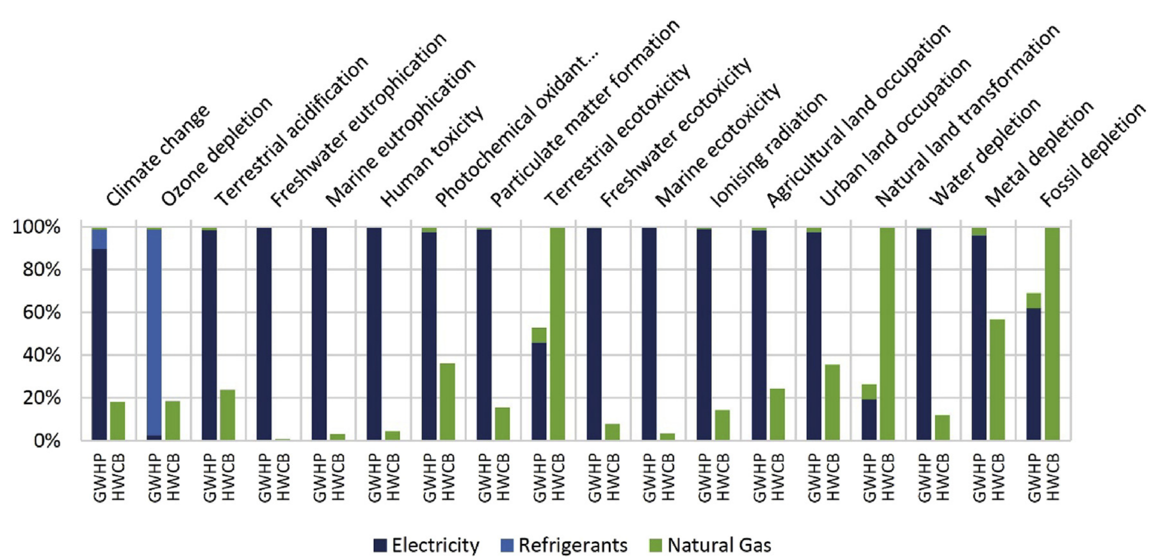

Fig. 14. ReCiPe midpoint impact indicators for the ground water heat pump (GWHP) system and the hot water condensing boiler (HWCB) system, normalized to the higher contributor in each impact category.

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and electricity. Other positive economic indicators included the internal rate of return on investment which varied from 33% to 38% depending on the variations in energy savings predictions. The simple payback period was found to be 2.1 years and the discounted payback period 4.9 years. A sensitivity analysis proved that proposed GWHP integration are even more profitable if the energy prices increase. For example, an increase in the natural gas unit price by 30% would reduce the SPB by 40%.

Although there were clear energy and economic benefits found for the proposed GWHP system, the LCA of the two systems for a 30-year time horizon revealed that the GWHP system would have worse effects on the environment. The existing natural gas driven system was found to have lower impacts across all impact indicators but terrestrial eco-toxicity, natural land transformation and fossil depletion. In the climate change impact category, the existing system's impacts were found to be 82% lower than those of the proposed GWHP system. Environmental implications are unfavorable due to the current grid electricity supply mix in the Republic of Serbia, but with potential environmental benefits if electricity is supplied from renewable sources and refrigerant leakage is reduced.

The case study findings can provide guidance for the Serbian DHS operators and policy makers, while the general approach presented in this study can also be replicated for the assessment of similar systems in other locations.

Further research could be dedicated to enhancement of the demand side management and facility management, by taking into account all of the technical, economic and environmental aspects. Such work would likely further promote a more sustainable urban residential development.

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